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The Annihilation of Galactic Positrons

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THE ANNIHILATION OF GALACTIC POSITRONS

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Abstract

We have studied the annihilation of galactic positrons in order to evaluate the probabilities of various channels of annihilation and to calculate the spectrum of the resulting radiation. The narrow width (FWHM < 3.2 keV) of the 0.511 MeV line observed from the Galactic Center (Leventhal et al. 1978) implies that a large fraction of positrons should annihilate in a medium of temperature less than 10^5K and ionization fraction greater than 0.05. HII regions at the Galactic Center could be possible sites of annihilation.

I. INTRODUCTION

Leventhal, McCallum and Stang (1978) have recently reported observation of positron annihilation radiation from the Galactic Center using a balloon borne germanium detector. The observed line is at 510.7 $\pm$0.5 keV, and its full width at half maximum (FWHM) is less than 3.2 keV. There is also some evidence for the three-photon continuum from triplet positronium annihilation. The 0.511 MeV line was previously seen from the solar flares of 1972, August 4 and 7 (Chupp, Forrest and Suri 1975), but because the lower energy resolution of the NaI detector used, only an upper limit of about 40 keV could be set on the line width from this observation.

Depending on the temperature and density of the ambient medium, positrons and electrons can either annihilate directly or form positronium. The importance of positronium formation in the interstellar medium was pointed out by Steigman (1968), by Stecker (1969), and by Leventhal (1973), and positron annihilation in solar flares, both direct and via positronium, has been treated by Crannell et al. (1976). Positronium can form either in the singlet state which annihilates into two 0.511 MeV photons, or in the triplet state which decays by 3 photon annihilation.

Positronium is formed by both radiative recombination with free electrons and charge exchange with neutral hydrogen (atomic or molecular). Charge exchange with heavier ions is much less important than these processes (Crannell et al. 1976). Once formed in a particular spin state, positronium in the interstellar medium annihilates from the same state, because the lifetimes of both singlet and triplet positronium (10^{-10} sec and 10^{-7} sec, respectively) are much shorter than typical collision times with interstellar gas.

Sources of galactic positrons are expected to be energetic particle interactions, long-lived radioactive nuclei from supernova explosions, and pulsars (see review by Lingenfelter and Ramaty 1978). All these sources produce positrons at relativistic energies.

Except for ultrarelativistic positrons, the probability for annihilation in flight is negligible until the positrons slow down to energies of the order of several hundred eV. (Ultrarelativistic positrons have a small probability $\sim 10\%$, for annihilating in flight, but these annihilations produce only a broad continuum which in general cannot be observed above other continua.) The purpose of the present paper is to investigate the annihilation process at energies below a few hundred eV. At these energies positrons either form positronium in flight or thermalize. The importance of free electrons in thermalizing positrons was first pointed out by Crannell et al. (1976).

In Section II we discuss the energy loss processes of positrons in a partially ionized medium, and the charge exchange cross section with neutral hydrogen; in Section III we calculate, using a Monte Carlo simulation, the probability of positronium formation in flight in a partially ionized gas as a function of temperature, density and degree of ionization; in Section IV we present the rates of direct annihilation and positronium formation of thermal positrons as a function of the temperature; in Section V we calculate line shapes resulting from positronium formation in flight and after thermalization; in Section VI we discuss the implications of the observed line width on the site of positron annihilation in the Galaxy; and we summarize our results in Section VII.

II. Energy Losses and Charge Exchange of Positrons

When a positron is injected into a partially ionized medium, it loses energy to the ionized component by exciting plasma waves and to the neutral component by the excitation and ionization of hydrogen atoms and molecules. The energy loss rate in the plasma, measured in eV/cm, is given by (Book and Ali 1975)

$$dE/d\ell = 1.3\times10^{-13}\, n_e (M(E/kT) - M'\, (E/kT))\, E^{-1} \ell n\Lambda, \tag{1}$$

where E is the positron energy in eV, n_e is the electron density in cm^{-3}, T is the temperature of the electrons in the plasma,

$$M(E/kT) = 2/\sqrt{\pi} \int_0^{E/kT} dx\, x^{1/2} e^{-x}, \tag{2}$$

$$\Lambda = (kT/4\pi m_e e^2)^{1/2}/\max(2e^2/(m_e u^2),\ h/(m_e u)), \tag{3}$$

$$u = (2E/m_e)^{1/2} - (8kT/\pi m_e))^{1/2} \tag{4}$$

and M' is the derivative of M with respect to its argument.

Unlike in a plasma where the energy loss process is essentially continuous, in a neutral medium the positron loses a significant fraction of its energy whenever it excites or ionizes an atom or molecule. The cross sections for ionizing atomic hydrogen and exciting its 2p level from the ground state by electrons are shown by solid lines in Figure 1 (Kieffer 1969). The cross sections for exciting other levels are small in comparison to that for the 2p level (Kieffer 1969, Moisewitch and Smith 1968), and are not expected to contribute significantly to the energy loss. We assume that the cross sections of these processes for positrons are the same as for electrons. Also shown by a solid line in Figure 1 is the cross section for positronium formation by charge exchange with atomic hydrogen (Drachman, Omidvar and McGuire 1978)

The dashed lines in Figure 1 are positron cross sections in molecular

hydrogen. The total cross section is from laboratory measurements made by Kauppila et al. (1977). (Similar measurements by Coleman, Griffith, and Heyland (1974) give somewhat lower values). The ionization cross-section is from the compilation of Kieffer and Dunn (1966). For the charge exchange cross section above 50 eV, we use the calculation of Sural and Mukherjee (1970), while below 20 eV, we have estimated this cross section by subtracting from the total the excitation and dissociation cross section given by Rescigno et al. (1976) and the elastic scattering cross section of Hara (1974). We then connected the point at 20 eV with that at 50 eV as shown in Figure 1. We assume that above 20 eV, the difference between the total cross section and the sum of those for ionization and charge exchange is the excitation and dissociation cross section of molecular hydrogen by positrons.

In atomic hydrogen, the energy lost in an excitation collision is 10.2 eV. For ionization, the mean energy of the ejected electron is 1/4 of its binding energy, and the distribution of the ejected electron velocities can be approximated by a Gaussian with standard deviation 0.382 αc ($\alpha = 1/137$) (Omidvar 1965). In molecular hydrogen, we assume an energy loss of 12 eV in an excitation and dissociation collision (Herzberg 1950) and we take the same distribution of the ejected electrons as in atomic hydrogen except for the different binding energy.

III. Positronium Formation in Flight

We consider a positron of energy E_o injected into a partially ionized hydrogen gas of temperature T and ionization fraction $X = n_e/(n_e+n_H)$, where n_e and n_H are the electron and neutral hydrogen densities. If the temperature of the ambient medium is of order 10^5K or larger, the positrons will thermalize before forming positronium. If, however, the temperature is lower,

then some fraction or the positrons from positronium in flight by charge exchange with neutral hydrogen. To evaluate this fraction, we have performed a Monte Carlo simulation in atomic hydrogen with ionization fraction X and $T < 10^5$K. Slowing down of positrons in molecular hydrogen is treated separately below.

We then allow the positron to lose energy continuously to the ionized component until it makes an inelastic collision with a hydrogen atom. The energy, E_1, at which this collision takes place is determined from

$$R = \exp\left[- \int_{E_1}^{E_1} \frac{n_H \, \sigma dE}{dE/d\ell}\right], \tag{5}$$

where R is a uniformly distributed random number, $dE/d\ell$ is given by equations (1) through (4), and σ is the sum of the ionization, excitation and charge exchange cross sections in atomic hydrogen shown in Figure 1. The probability that any one of these processes occurs at E_1 is proportional to its cross-section at this energy. If positronium is formed, we remove the positron from the calculation because positronium in both the singlet and triplet states is expected to annihilate in a time much shorter than its collision time in the interstellar medium. In an excitation or ionization collision on the other hand, the positron loses energy as discussed in Section II. After an excitation or ionization we repeat the process specified by equation (5) with a new value for E_o given by the difference between E_1 and the energy lost in the collision, and we continue this procedure until either positronium is formed or the energy falls below the positronium formation threshold.

The fraction of positrons which form positronium in flight before thermalizing, f_{ps}, is shown in Figure 2 as a function of X for two cases: $n_e = 0.1\text{cm}^{-3}$, T = 8000K and $n_e = 5\text{x}10^{13}\text{cm}^{-3}$, $T = 1.16\text{x}10^4$K. The parameters

of the first case could be representative of the warm component of the interstellar medium (McKee and Ostriker 1977), while those of the second case are essentially the same as the values considered by Crannell et al. (1976) for solar flares. The fraction of positrons forming positronium in flight increases with decreasing ionization fraction; for the interstellar case and $X < 0.05$ more than half the positrons form positronium before they thermalize. If $n_e = 0$, about 95% of the positrons form positronium in flight. We also see that f_{ps} increases with increasing electron density because of the reduction of the energy loss rate to the plasma due to the reduction of the Coulomb logarithm, whose argument is given in equation (3). We have calculated f_{ps} for temperatures other than shown in Figure 2, and we find that it varies by less than 20% for $T < 6x10^4$K. For higher temperatures, f_{ps} is expected to be small in any case because of the absence of neutral hydrogen.

We have compared the results of Figure 2 with the calculations of Crannell et al., (1976) and we find that for $X = 0.5$, our f_{ps} is smaller by about a factor of 2 than theirs (see Figure 4 in Crannell et al. 1976). This results from an erroneous factor of 2 in the Fokker-Planck equation that was used by them to treat the slowing down of positrons in a partially ionized plasma (G. Joyce, private communication 1978). For $X = 0.09$, the discrepancy is much smaller because in this case, energy loss to the plasma is less important relative to charge exchange. We wish to note that for low values of X, the effect of the neutrals on the energy loss becomes important; for example, for $X = 0.09$, neglecting the neutrals would increase f_{ps} by about 20%.

We do not expect molecular hydrogen in a phase of the interstellar medium

with high temperature and high ionization fraction. For molecular hydrogen, therefore, we only evaluate f_{ps} for $n_e = 0$. Using the same Monte Carlo simulation as for atomic hydrogen and the cross sections of Figure 1, we obtain $f_{ps} = 0.93$. This value is slightly lower than f_{ps} in atomic hydrogen at $n_e = 0$ because of the higher threshold for positronium formation in the molecular case. We note, however, that this result is somewhat uncertain because of the cross sections that we have assumed.

IV. The Fate of Thermal Positrons

Having evaluated the fraction of positrons that form positronium in flight, we now consider the fate of those positrons which thermalize before annihilation. Thermal positrons will eventually form positronium or annihilate directly, and both these processes can occur with either bound or free electrons. Positronium formation with free electrons is radiative recombination. Radiative recombination and direct annihilation rates with free electrons were calculated by Crannell et al. (1976); we have extended these calculations to lower temperatures, and the results are shown in Figure 3. The direct annihilation rates with atomic electrons shown in this figure was obtained by using the cross section for direct annihilation, equation (3) in Crannell et al. (1976). We let the relative velocity between the electron and positron be αc; this yields $R_{da}/n_H = 2\pi^2 r_o^2 c$.

The rate of charge exchange of thermal positrons with residual neutral hydrogen can be calculated by assuming that the positrons are in thermal equilibrium with the ambient medium. This is justified because even though annihilation and positronium formation tend to modify the positron distribution, the rate of reestablishing thermal equilibrium is much faster than the sum of the rates of all annihilation processes. Therefore, the rate of charge

exchange of thermal positrons can be written as

$$R_{ce}/n_H = \int_{6.8eV}^{\infty} n_{MB}(E)\sigma_{ce}(E)\, v(E)dE, \tag{6}$$

where n_{MB} is the Maxwell-Boltzmann distribution, and σ_{ce} is the charge exchange cross section with atomic hydrogen shown in Figure 1. We have evaluated equation (6), and the results are shown in Figure 3. As can be seen, this rate is a very strong function of temperature, but even at its maximum, it is lower than the thermalization rate (Spitzer 1962).

From Figure 3 we see that for temperatures greater than 10^6K, the dominant annihilation process is direct annihilation with free electrons. At lower temperatures, radiative recombination becomes more important than direct annihilation, but depending on the amount of residual neutral hydrogen present, charge exchange may in fact be the most important process. For example, at $T = 10^5$K, the rate of charge exchange is greater than that of radiative recombination if $n_H/n_e > 5\times10^{-6}$. Since for temperatures less than 10^5K, we expect larger neutral hydrogen concentrations, charge exchange should be the dominant process down to temperatures around 10^4K. At 8000 K, $R_{ce}/n_H = R_{rr}/n_e$, so that if, for example, the medium is half ionized (e.g. the warm ionized component of the interstellar medium, McKee and Ostriker 1977), the rates of charge exchange and radiative recombination are about equal. At lower temperatures, radiative recombination should remain the dominant process as long as there is an appreciable concentration of free electrons. However if n_e/n_H becomes small, a large fraction of the positrons form positronium in flight, as can be seen from Figure 2.

From Figure 3 we also see that there is a finite probability for direct annihilation even when positronium formation is the dominant process. For example, at T = 8000K and $n_e = n_H$, about 7% of the positrons will

annihilate directly (mostly with free electrons).

V. The Energy Spectrum of Positron Annihilation Radiation

In this section, we evaluate the energy spectrum of positron annihilation radiation resulting from positronium formation in flight and from the annihilation of thermal positrons. We first consider annihilation in flight. Using the Monte Carlo simulation described in Section III, we calculate the photon spectrum in molecular hydrogen with $n_e = 0$ and in atomic hydrogen with X = 0 and 0.1. As can be seen from Figure 2, for more ionization only a small fraction of the positrons form positronium in flight.

The probabilities for forming positronium in the singlet or triplet state are 0.25 and 0.75, respectively. Annihilation from the singlet state produces two photons of 0.511 MeV in the rest frame of the positronium. In the frame of the galaxy, the energy of a photon from such an annihilation is

$$\varepsilon_\gamma = \varepsilon_o \ (1-\beta\cos\theta^*)/(1-\beta^2)^{1/2}, \qquad (7)$$

where ε_o = 0.511 MeV, β is the velocity of the positronium, and θ^* is the angle between the positronium velocity and the photon direction in the positronium rest frame. We assume that the photon direction is isotropic in this frame. Annihilation from the triplet state produces three photons whose energies can also be obtained from equation (7) provided that ε_o is replaced by ε^* which is chosen according to the distribution given by Ore and Powell (1949).

The results are shown in panels a, b, and c of Figure 4. There is little difference between the line shapes for the atomic and molecular cases with $n_e = 0$. The full width at half maximum for both these cases is about 6.5 keV. The line shape for 10% ionization fraction has a flatter top than those for $n_e = 0$, because in this case the rapid energy losses cause the

spectrum of the positronium formed to cut off sharply at low energies. The width of the line for $X = 0.1$ is about 7 keV. The effect of the three photon annihilation is manifest in a slight asymmetry in the line shape and a low energy tail.

In the case of annihilation of thermal positrons, the shape of the 0.511 MeV line from both singlet positronium annihilation following radiative recombination and direct annihilation with free electrons is expected to be a Gaussian of FWHM $\simeq 0.011$ (keV) $(T(K))^{1/2}$ (Crannell et al. 1976). For example, if $T = 10^4$K, the width is 1.1 keV. For direct annihilation with atomic electrons, the line shape is determined by the motion of the bound electrons and we expect a FWHM of about 7.5 keV.

The photon spectra, $q(\varepsilon_\gamma)$, resulting from charge exchange of thermal positrons was calculated as follows: for annihilation from the singlet state

$$q(\varepsilon_\gamma) = \int_{E_1}^{\infty} dE\, n_{MB}(E)\, \sigma_{ce}(E) v / ((E-6.8\text{eV})(E-6.8\text{eV} + 4\varepsilon_o))^{1/2}, \tag{8}$$

where $E_1 = (\varepsilon_\gamma - \varepsilon_o)^2/\varepsilon_\gamma + 6.8$ eV, while for the triplet,

$$q(\varepsilon_\gamma) = \int_{E_2}^{\infty} dE\, n_{MB}(E)\, \sigma_{ce}(E) v / ((E-6.8\text{eV})(E-6.8\text{eV} + 4\varepsilon_o))^{1/2} \int_{x_1}^{x_2} dx\, P_t(x)/x \tag{9}$$

where

$$E_2 = \begin{cases} E_1 & \text{for } \varepsilon_\gamma > \varepsilon_o \\ 6.8\text{eV} & \text{for } \varepsilon_\gamma \le \varepsilon_o. \end{cases}$$

For equation (8), $P_t(x)$ is the distribution of Ore and Powell (1949) with $x = \varepsilon_\gamma^*/\varepsilon_o$, $x_1 = \varepsilon_\gamma/(\varepsilon_o(1+\beta))$, and $x_2 = \min(1, \varepsilon_\gamma/(\gamma\varepsilon_o(1-\beta)))$, where γ and β are the Lorentz factor and velocity (divided by c) of the positronium atom formed, corresponding to (E -6.8 eV).

By combining the results of equations (8) and (9), we have plotted in panel d of Figure 4 photon spectra from thermal positron annihilation for T = 8000K and 50000K. The FWHM's for these two cases are about 1.5 and 3.2 keV, respectively.

VI. Discussion

As we have pointed out in the Introduction, the FWHM of the 0.511 MeV line from the Galactic Center was observed to be less than 3.2 keV (Leventhal et al. 1978). When compared with the line shapes shown in Figure 4, this width is inconsistent with positronium formation in flight, and therefore requires that at least some of the positrons thermalize before they annihilate. The temperature of the medium in which they thermalize should not exceed about 10^5K, since otherwise the line would be broader than observed, and the medium should be substantially ionized, so that a large fraction of the positrons thermalize (see Figure 2).

If we consider the three component model of the interstellar medium (McKee and Ostriker 1977), then the most acceptable sites of annihilation are the warm neutral and the warm ionized media, whose temperatures are about 8000K and ionization fractions are 0.15 and 0.68, respectively. For this temperature, the width of the line is only $\sim$ 1.5 keV, and, as can be seen from Figure 2, 80% and 98% of the positrons thermalize for these choices of ionization fractions. The bulk of the positrons should not annihilate in cold clouds even though most of the interstellar matter is beleived to be in them. Since n_e/n_H is very low in clouds ($< 10^{-5}$, Guélin et al. 1977), the line width would be larger than observed. Neither should they annihilate in the hot component whose temperature is about $5x10^5$K and density $3x10^{-3}cm^3$; however, we do not expect much annihilation in this medium in any case, because the annihilation time is on the order of $3x10^8$ years, and in this time, the positrons are expected to encounter the denser clouds in which their annihilation time is much shorter.

Other possible annihilation sites are young supernova remnants. For

example in the filaments of the Crab Nebula, $n_e \simeq n_H$ and $T_e \leq 10^4$K (Davidson and Tucker 1971). Supernovae are also likely sources of positrons through all the processes mentioned in the Introduction.

The 0.511 MeV line was observed from the direction of the Galactic Center, but because of the wide opening angle of the detector (~ 15°) the field of view included a large portion of the Galactic Center region extending to the expanding arm of 135 km/sec (Mezger 1974). If the positron source, however, is located at the nucleus of the Galaxy, the positrons would thermalize and annihilate in the extended HII region in the nuclear disk, even though most of the diffuse matter is in the 270 pc molecular ring (Scoville 1972) encircling this region (Mezger 1974). The ionized region has an electron density of 15 to 30 cm^{-3} and temperature less than 10^4K. From equations (1) through (4), we expect positrons with initial energies of several hundred keV to traverse a total distance of about 500 pc in about 2000 years before they thermalize. Because of scattering, however, the rectilinear distance could be much smaller, and therefore the positrons would annihilate before reaching the molecular ring. The annihilation time in the ionized medium is about 10^3 years. For the temperature of this medium, the width of the line is less than about 1.5 keV, consistent with the observed upper limit of 3.2 keV.

VII. Summary

We have investigated the annihilation of galactic positrons, and the formation of the 0.511 MeV line and the accompanying 3-photon positronium continuum. In a cold and neutral medium, about 95% of the positrons form positronium atoms in flight and these atoms annihilate before undergoing further collisions if the density of the medium is less than $\sim 10^{15} cm^{-3}$. The shape of the 0.511 MeV line from positronium formed in flight is broad, with FWHM $\simeq$ 6.5 keV (Figure 4). The width appears to be inconsistent with

the observed width of the 0.511 MeV line from the Galactic Center (< 3.2 keV), Leventhal et al. 1978).

In a warm, partially ionized gas of temperature less than several times 10^4K, only a fraction of the positrons form positronium in flight and this fraction decreases with increasing n_e/n_H (Figure 2). At higher temperatures, essentially all the positrons thermalize before forming positronium or annihilating directly.

The rates for the various processes leading to positron annihilation are shown in Figure 3. For temperatures less than $\sim 10^6$K, positronium formation is the dominant annihilation channel, while for higher temperatures free annihilation dominates. The width of the 0.511 MeV line from thermal positron annihilation is about 3 keV for $T \simeq 10^5$K and varies as $T^{1/2}$. The observed width from the Galactic Center implies a temperature less than this value, and a degree of ionization larger than about 5%, for which half the positrons thermalize. For these conditions more than 90% of the positrons annihilate after forming positronium, and this is consistent with the possible evidence for 3-photon continuum found by Leventhal et al. (1978).

Among the various galactic sites, the warm component of the interstellar medium, filaments or knots in supernova remnants, and the extended HII region in the nuclear disk could be sites for forming the 0.511 MeV line from positron annihilation.

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Figure Captions

Figure 1. Cross sections for charge exchange, excitation and ionization in atomic hydrogen (solid lines), and the total cross section, cross sections for ionization and charge exchange in molecular hydrogen (dashed lines) as a function of positron energy.

Figure 2. The fraction of positrons forming positronium atoms before thermalizing, by charge exchange with atomic hydrogen as a function of the ionization fraction of the gas for two sets of parameters.

Figure 3. The rates (per unit target density) at which thermal positrons form positronium by charge exchange with neutral H (R_{ce}/n_H) or by radiative recombination with free electrons (R_{rr}/n_e), and annihilate directly with free electrons (R_{da}/n_e) or with bound electrons (R_{da}/n_H), as functions of the gas temperature

Figure 4. The calculated profiles of the 0.511 MeV positron annihilation line. Panels (a), (b), and (c) show the profile from positronium formation in flight in neutral molecular, neutral atomic, and in a mixture of 90% atomic and 10% ionized hydrogen, respectively. Panel (d) shows the profile from charge exchange after thermalization of the positrons with residual neutral hydrogen in the 10% ionized case. All of these spectra include the contribution of the 3-photon annihilation of triplet positronium.

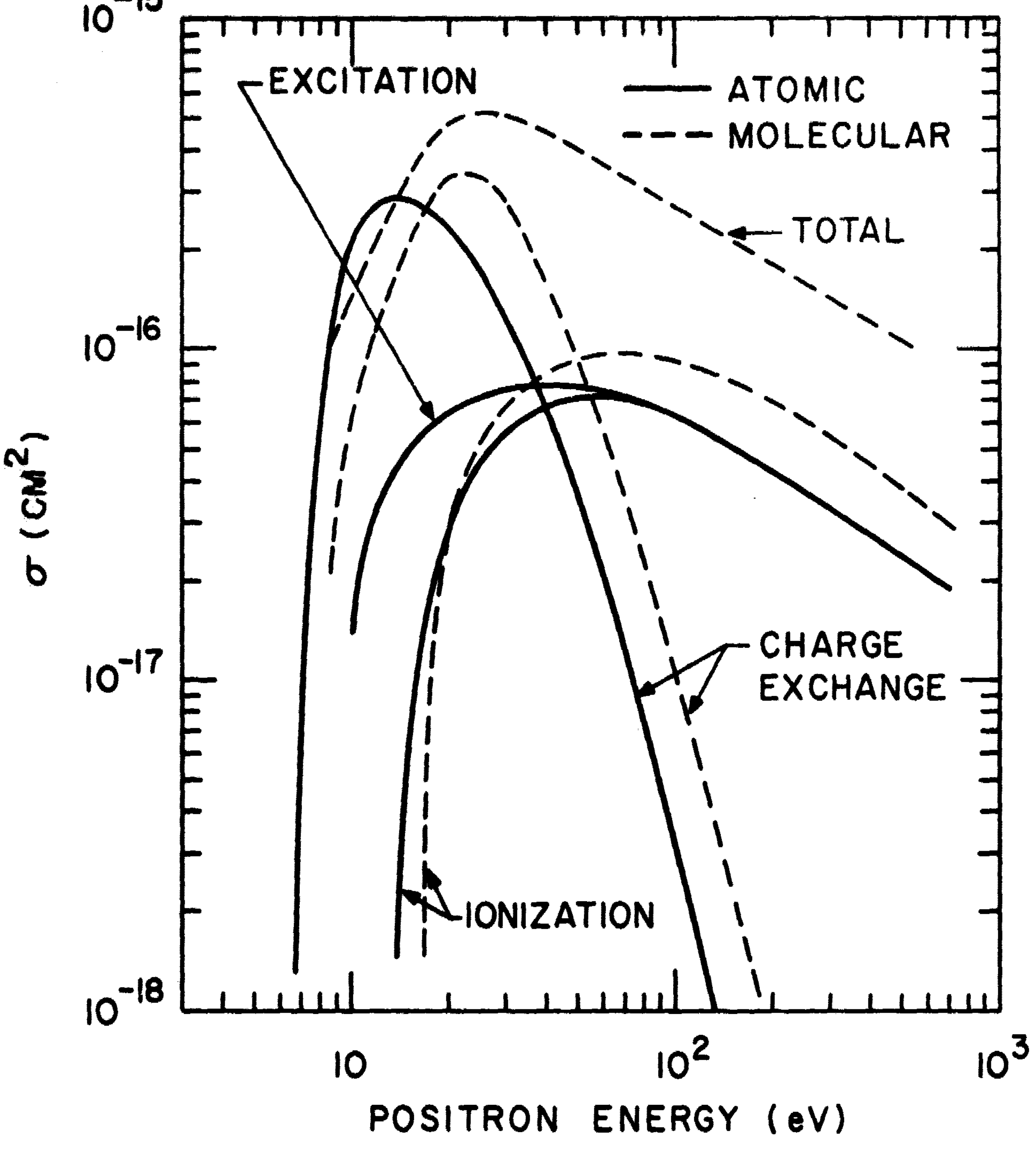
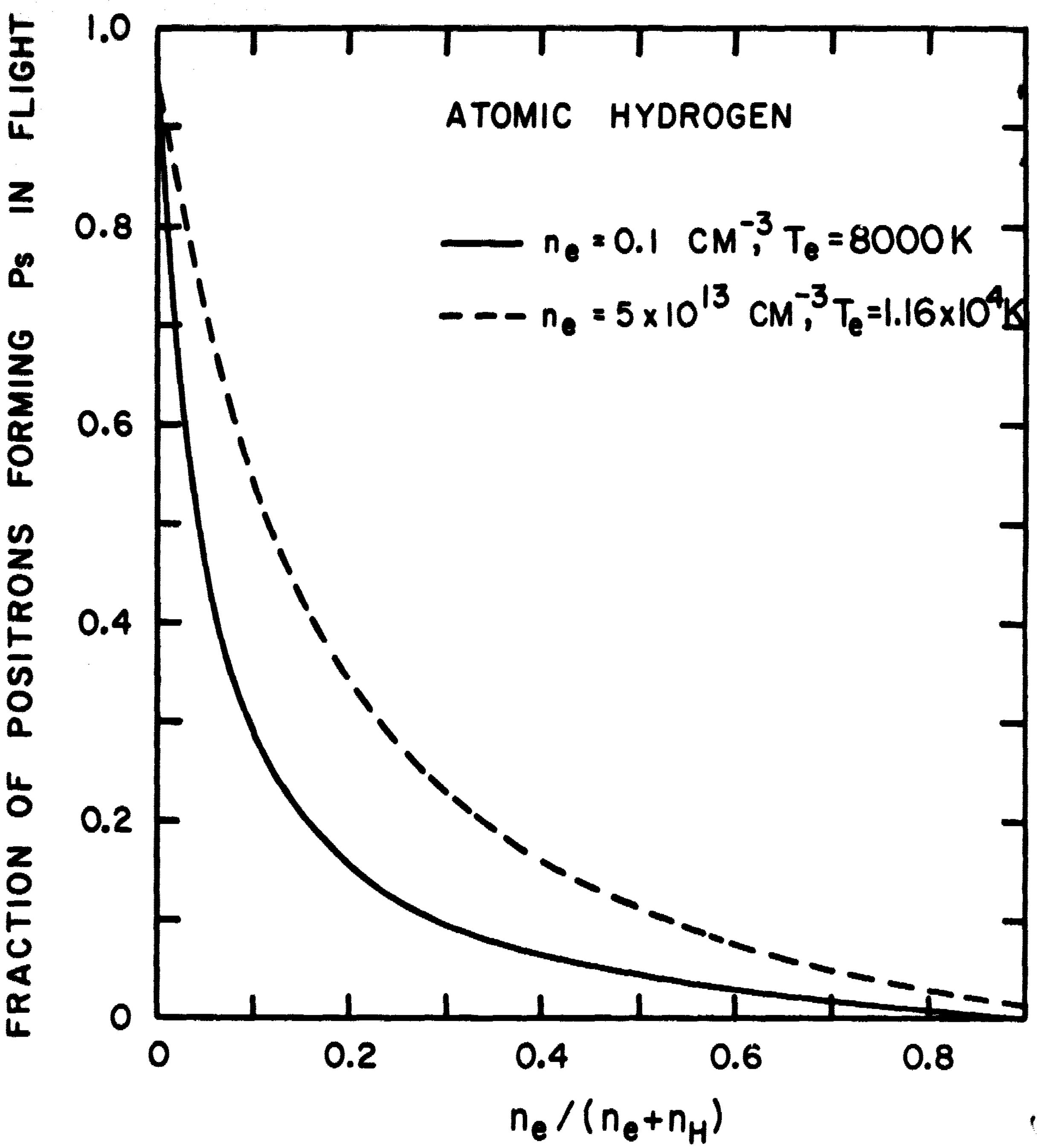
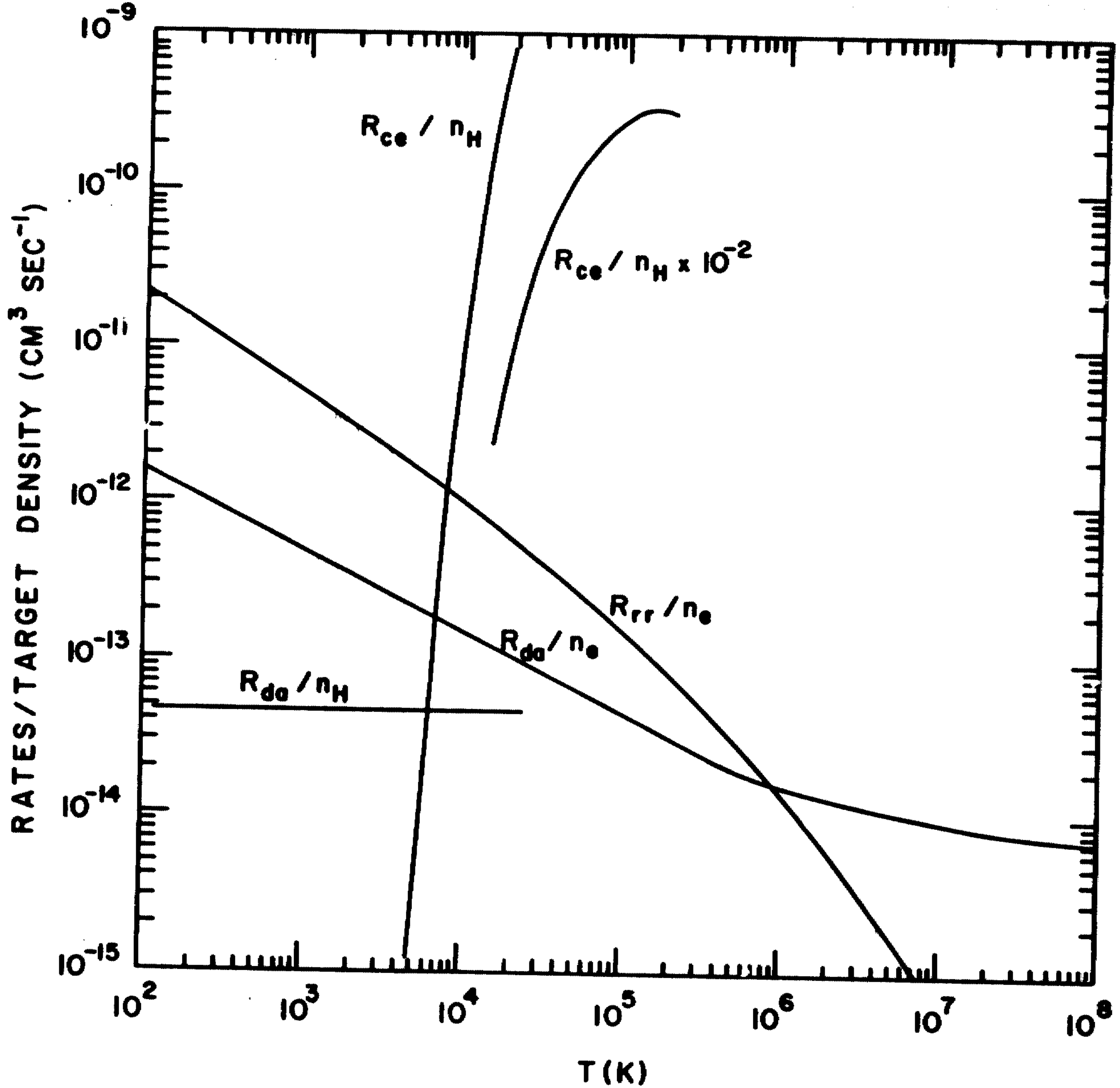

10^{-15}
10^{-16}
10^{-17}
10^{-18}
σ (CM^2)
EXCITATION
ATOMIC
MOLECULAR
TOTAL
CHARGE
EXCHANGE
IONIZATION
10
10^2
10^3
POSITRON ENERGY (eV)

Figure 1



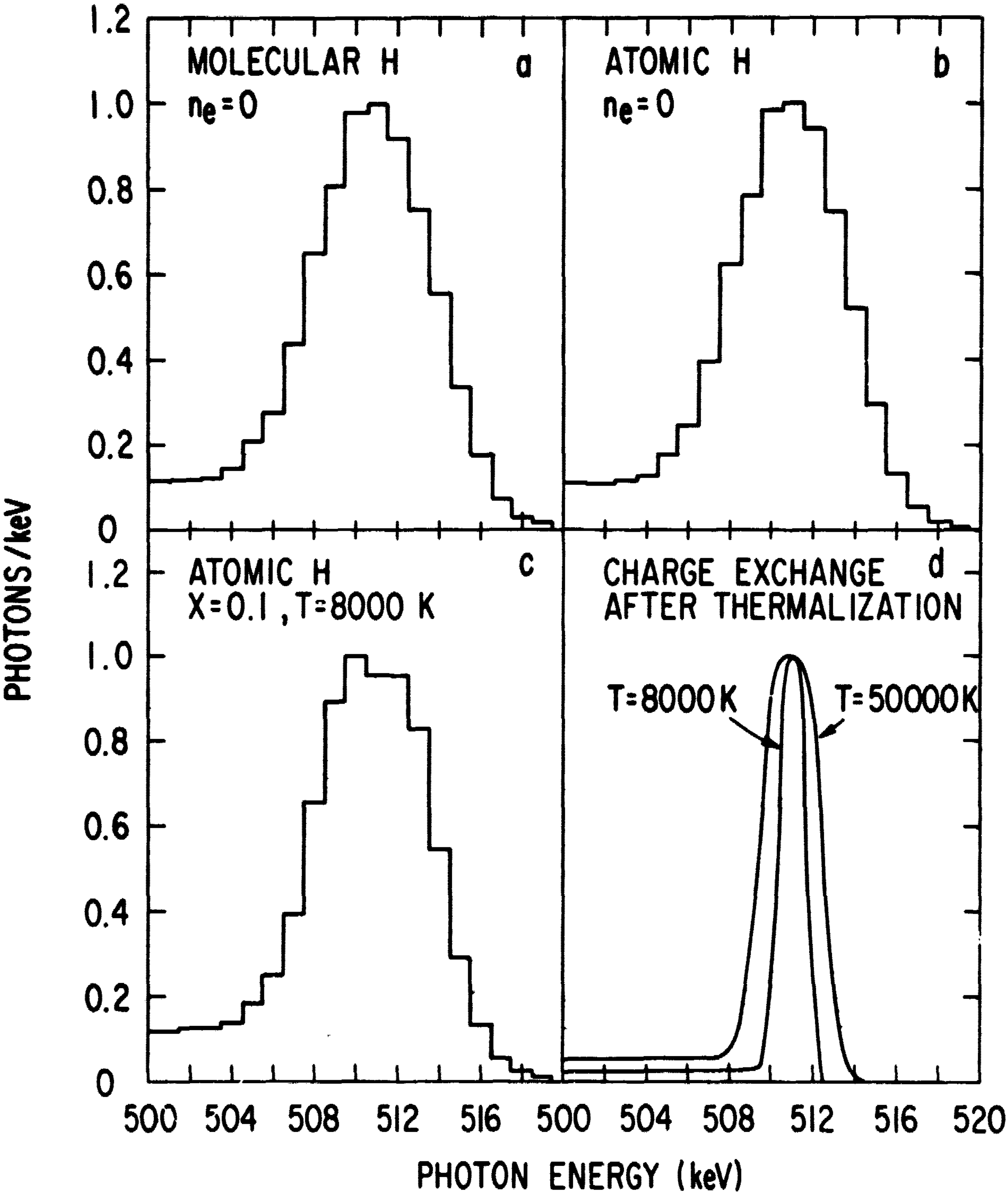
ATOMIC HYDROGEN
$n_e = 0.1$ CM^{-3}; $T_e = 8000$ K
$n_e = 5 \times 10^{13}$ CM^{-3}; $T_e = 1.16 \times 10^4$ K
FRACTION OF POSITRONS FORMING Ps IN FLIGHT
$n_e/(n_e+n_H)$
1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8

Figure 2



RATES/TARGET DENSITY (CM^3 SEC^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
R_{ce} / n_H
R_{ce} / n_H x 10^{-2}
R_{rr} / n_e
R_{da} / n_e
R_{da} / n_H
10^2
10^3
10^4
10^5
10^6
10^7
10^8
T (K)

Figure 3



MOLECULAR H
n_e=0
a
ATOMIC H
n_e=0
b
ATOMIC H
X=0.1 , T=8000 K
c
CHARGE EXCHANGE
AFTER THERMALIZATION
d
T=8000 K
T=50000 K
PHOTONS /keV
1.2
1.0
0.8
0.6
0.4
0.2
0
500
504
508
512
516
520
PHOTON ENERGY (keV)

Figure 4

BIBLIOGRAPHIC DATA SHEET

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM 79600		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
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